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SAMPLING TECHNIQUES**

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ABSTRACT

Two rockets were flown to peak altitudes of 220 km in Sept 1959 to test various methods planned for the future measurements of the ionization parameters in the ionosphere, exosphere and interplanetary plasma. All the experiments described used techniques which sample the ambient environment in the immediate vicinity of the research vehicle. These direct methods were chosen, since indirect propagation techniques do not provide the temperatures of charged particles, are insensitive to ion densities, and cannot measure local electron densities under all conditions. Very encouraging results have been obtained from a preliminary analysis of the data from one of the two flights.

A new rf probe technique was successfully used to determine the electron density profile as indicated by its agreement with the results of a companion cw propagation experiment, particularly when the probe data are corrected

for the effects of the ion sheath which surrounds the vehicle. The characteristics of this sheath were determined directly in flight by an electric field meter which provided the sheath field, and by a Langmuir probe which measured the total potential across the sheath.

Electron temperatures deduced from the Langmuir probe are greater than the neutral gas temperature values previously measured for the same location and season, but possibly under different atmospheric conditions. Ion densities were calculated from the ion trap data for several altitudes ranging from 130 to 270 km and were found to be within 20 percent of the measured electron densities.

INTRODUCTION

A comprehensive study of the nature of ionization in the regions of space requires simultaneous measurements of the following parameters: the electron and ion concentration, their thermal energies and the ion composition.

The vertical electron density profile of the undisturbed ionosphere is fairly well known up to the height of the maximum electron density ($h_{\max} F_2$), usually about 300 to 400 km above the earth's surface. Typical profiles were first established from rocket measurements, using Seddon's cw propagation experiments [Seddon, 1953]. These data resolved ambiguities present in P'-f ground observations [Jackson, 1956], and "bottomside" profiles can now be obtained from many locations.

Relatively little is known concerning the disturbed ionosphere below $h_{\max} F_2$, about the topside ionosphere, the exosphere and the interplanetary plasma. Uncertainties by a factor of 10 are common regarding ionospheric irregularities or electron densities in the upper ionosphere. Yet electron densities are by far the best known ionospheric parameter.

Although ion composition measurements are not discussed in the present paper, it can be stated that present techniques can provide ion composition for altitudes ranging from 100 up to about 5000 km. New techniques are needed, however, to

investigate the other ionospheric parameters mentioned earlier. Furthermore past investigations were usually limited to measurements of one or at most two parameters during a given rocket flight. Thus a great need still exists for simultaneous measurements.

Environmental sampling methods have been used extensively for investigations in the various scientific disciplines of space research. Although past rocket studies of the ionosphere seem to have favored indirect methods, the need for ionospheric measurements at any location and under any condition dictates the use of environmental sampling techniques. Radio propagation methods cannot meet these broad objectives, since they measure only one ionization parameter and even then become severely handicapped [Jackson and Seddon, 1954], if not completely useless, when irregularities are present in the ionosphere. The major disadvantage of the environmental methods is their sensitivity to local disturbances produced in the immediate neighborhood of the space vehicle. With proper precautions the local contamination can be minimized and with a competent evaluation of the remaining local effects, accurate results can be obtained.

Two rocket flights were recently conducted for the specific purpose of testing several direct sampling methods which are being developed for synoptic investigations of

ionospheric parameters. Both flights were successful. Preliminary results from only the second and more successful of the two is reported here. This rocket (NASA 4.07), an Aerobee-Hi, was flown in the auroral zone to an altitude of 220 km at midday on September 14, 1959.

In order to check the electron density measurements, the rockets were launched into a uniform ionosphere, under which condition a fairly accurate profile can be calculated from ground P'-f soundings. In addition, Seddon's cw propagation experiment was included in the rocket instrumentation, since it provides reliable results for rocket soundings into a quiet ionosphere. The environmental sampling sensors which were investigated include a radio-frequency impedance probe, an ion trap, a Langmuir probe, and an electric field meter. These measure respectively electron concentration, ion density, electron temperature and vehicle surface charge density. Each of the above sensors can in general measure more than one parameter, but they are best suited for the individual measurements indicated above.

The locations of the instruments on the rocket nose cone are pictured in Figures 1 and 2. The rocket-borne cw propagation transmitter was deactivated periodically and consequently the resulting electron density profile was obtained in dashed form. This was done so that the direct measurements

data could be obtained in the presence of minimum radio-frequency field disturbances. Assurance of quiet ionospheric conditions was obtained by continuous monitoring from ground-based P'-f stations. The ionosphere was especially uniform during the flight which occurred one hour subsequent to a radio blackout. This was evidenced by the complete lack of distortion of the beat notes recorded by the cw propagation receivers. Optical and magnetic aspect were measured throughout the flight. The latter data showed that the rocket was essentially vertically oriented during flight.

The R. F. Impedance Probe Experiment

The rf probe experiment was devised as a result of several rocket flights in which were observed the effect of the ionosphere upon the performance of low frequency rocket-borne antennas. It was found that the antenna capacitance changed by an amount proportional to the ambient electron density. However the effects noted yielded electron densities too small by a factor of 3 [Jackson and Kane, 1959]. The discrepancy was attributed to the presence of large rf fields on the antenna. The correctness of this conclusion was established with the NASA 4.07 experiment, in which the use of low rf fields improved the accuracy of the measurements considerably.

The capacitive detuning of a rocket-borne probe consisting of two collinear whips each approximately 0.6 cm radius and 6.0 meters in length was measured at 7.75 mc. Assuming that in the ionosphere the probe capacitance C is related to the free-space capacitance C_0 by $C = KC_0$ permits the local electron density to be computed from the simplified Appleton-Hartree formula for dielectric constant $K = 1 - \frac{81N_e}{f^2}$ where N_e is the electron concentration per cc and f is the exploring frequency in kilocycles.

The electron densities obtained by the propagation and probe methods from NASA rocket flight 4.07 are compared in Figure 3. Both profiles are in agreement concerning the absence of a significant valley above the maximum of the E-region. The descent part of the propagation experiment has not yet been analyzed. Two general considerations must be taken into account in comparing the two methods: the ability to define the shape of the electron density profile under all flight conditions and the absolute accuracy of the derived electron concentrations. With regard to the first consideration, the data from the propagation experiment near the peak of the trajectory is not plotted because of unusable fluctuations due to the high horizontal and low vertical velocity components of the rocket. This reflects one disadvantage of this particular propagation experiment

for satellite applications. On the other hand, the cw propagation data which are plotted have errors of the order of only a few percent.

It is seen from Figure 3 that the propagation method yields electron densities that are greater than the results of the probe method by a ratio which varies from 1.2 at 100 km to about 1.5 at 210 km. This improvement over the previously reported factor of 3 disagreement between the two methods is due to the fact that the probe measurements were performed at a reduced rf power level. The remaining discrepancy is attributed to the effects on the probe method of vehicle induced disturbances, the most serious of which is the formation of an ion sheath enveloping the rocket and the probe. The discrepancy can be explained entirely by a probe-enclosing sheath whose thickness varies from 1.5 cm at 100 km to 3.5 cm at 210 km. Calculated values of the thickness of this sheath assuming charge diffusion under thermodynamic equilibrium to be the only contributing mechanism, are 1.1 cm at 100 km and 1.6 cm at 200 km. However, results discussed below from the other environmental sampling experiments in the NASA rocket show that larger sheath thicknesses than these can be expected.

The accuracy achieved with the rf probe experiment is already satisfactory for use in the disturbed ionosphere and for resolving orders of magnitude in the exosphere. If higher

accuracy is desired for other ionospheric studies, the absolute error can be reduced considerably by taking the sheath observations from the NASA rocket into account or by making further refinements in the experiment itself.

Theoretical and Experimental Evaluations of the Rocket's Ion Sheath.

In addition to measurements of the electron temperature and of the sheath field, the Langmuir probe and electric field meter data from the NASA rocket provide information on the characteristics of the rocket's ion sheath which explain the larger corrections needed for the rf probe experiment. It is of interest to compare the experimental sheath characteristics with the model derived from generally accepted kinetic theory.

In using kinetic theory, previous workers neglect photo-emission and the presence of rf fields. The theory considers a neutral plasma consisting of positive ions and electrons into which is inserted a plane conducting body. The body assumes a negative equilibrium potential due to the higher electron velocity and consequently is surrounded by a positive ion sheath. The electron current (I_e) which flows to the body is produced only by those electrons energetic enough to overcome the equilibrium potential. At equilibrium, the total current to the body is zero with I_e balanced by the relatively undisturbed positive ion current I_+ . The potential V_q is given by

$$V_q = \frac{kT_e}{2e} \ln \frac{T_e M_+}{T_+ M_e} \quad (1)$$

where k is Boltzmann's constant, T_e and T_+ the electron and ion temperatures and M_e and M_+ their masses. Assuming an ionic constituent of 28 AMU and thermodynamic equilibrium, this reduces to

$$V_q = 5.4 kT \quad (2)$$

where T is the kinetic gas temperature.

Expected values of V_q as a function of altitude are plotted in Figure 4. The curve was computed by averaging two kinetic gas temperature profiles [Horowitz and LaGow, 1958] obtained at the same latitude and during two months which bracket the NASA firing. The values are apt to be approximate because Eq. 2 assumes plane geometry and because the kinetic gas temperatures were obtained indirectly from scale-height measurements on the assumption that the gram molecular weight of air was 28.9 over the entire altitude range.

The thickness of the ion sheath surrounding the rf probe was computed from the rocket potential of Fig. 4, using an analytic relationship for cylindrical geometry [Jastrow and Pearse, 1957]. The values obtained, (1.1 cm at 100 km and 1.6 cm at 210 km) are not enough to completely explain the

difference between the cw propagation and the rf probe electron density results.

We shall consider now the model of the ion sheath as experimentally observed on the NASA rocket. First, measurements of current density made by the electric field meter when it was pointed at the sun show that for the altitudes considered here, the contribution of photoemission current to the total rocket potential can be neglected justifiably. Secondly, Langmuir probe data show rocket potentials which are about twice those plotted in Fig. 4. The higher rocket potential is attributed in part to the rectifying action of the telemetry and beacon antennae and in part to ambient electron temperatures higher than the kinetic gas temperatures of Horowitz and LaGow.

Parenthetically, sheath thicknesses computed from the measured potentials and sheath fields are of the order of 1 to 2 cm at the rocket body. These thicknesses should not be confused with those of the rf probe sheath since the geometry is different. The experimental sheath thickness data is presented here because some theoretical studies speculate sheath dimensions several times greater than this [Imyanitov, 1957], for altitudes between 100 and 200 km.

Unfortunately, the Langmuir probe measurements of rocket potential have not been analyzed completely so that point-by-point correction of the rf probe results based on experimental

values of this potential cannot be made at this time. However, the higher observed rocket potentials are in the right direction and of about the proper magnitude to explain the required rf probe corrections.

The Langmuir Probe Experiments

Direct measurements of electron temperatures are needed to resolve the important question of thermodynamic equilibrium. Electron temperatures have been measured indirectly from satellite observations of vehicle potential [Krassovsky, 1959] and directly by the use of a double-probe version of the Langmuir probe [Boggess and others, 1959].

The experiment conducted on the NASA rocket is the single-probe version of the Langmuir probe in which the current I_p to an exposed circular plate is measured as a function of the voltage V between the plate and the rocket skin. The work of Langmuir offers the theoretical background for the experiment which bears his name. The analysis performed thus far is illustrated in Fig. 5. Presented are a theoretical (A) and an experimental (B) curve corresponding to an altitude of 180 km, the theoretical curve being based on thermodynamic equilibrium, Maxwellian distribution of positive ion and electron energies, and Langmuir's simplified theory for plane geometry.

Considering first the theoretical curve for large negative values of V , I_p is a space-charge limited positive ion current given by

$$I_p = I_+ = \frac{N_+ e \bar{c}_+ A}{4} , \quad (3)$$

where \bar{c}_+ is the average ion velocity and A the effective collection area. In the region between the large negative and positive values of V , I_p is the sum of the electron and ion currents. The electron current in this region is given by

$$I_e = I_{e0} \left(e^{\frac{-Ve}{KT_e}} \right) , \quad (4)$$

where I_{e0} is the undisturbed electron diffusion current. A log plot of Eq. 4 yields a straight line, the slope of which is a measure of the electron temperature. This measurement is independent of the ambient electron density. For large positive values of V , the probe current is the space-charge limited electron current I_{e0} given by Eq. 3 with the signs reversed. The rocket potential due to diffusion alone (V_q) is given by the negative value of V read at the sharp break in the I - V curve, this being the point where the probe changes polarity with respect to the plasma.

The experimental curve in Fig. 5 is typical of the few volt-ampere curves examined thus far. Even the interpretation

of the individual curves is preliminary. The measured rocket potential of -1.7 volts is higher than the theoretical value of -1.1 volts at 180 km from Fig. 4. It is composed of two additive components V_a and V_q .

The bias or shift of the overall curve (V_a) is attributed to the rectifying action of the beacon and telemetry antennae. This shift should not affect the electron temperature measurement. The largest error in computing the temperature from the appropriate slope comes about in the correction which must be made for the positive ion current. For the curve shown, if a constant correction corresponding to the I_+ at the largest negative values of V is made, one computes an upper limit of approximately 7000°K for T_e at 180 km. Based on this assumption the upper limit for the observed electron temperatures over the altitude range averages twice the kinetic gas temperatures observed by Horowitz and LaGow. A more refined ion current correction based on the ion trap data could lead to lower electron temperatures. It is expected, however that the lower limit will still be in excess of the gas temperature reported by Horowitz and LaGow.

Even though data interpretation is preliminary; it is felt that ionospheric electron temperatures can be measured with plasma probes. This will provide one of the parameters required to resolve the question of thermodynamic equilibrium. The accuracy possibly can be improved by eliminating positive

ion current with the aid of an appropriately-biased grid placed in front of the collector. This modification has been suggested by E. C. Whipple, of NASA.

Measurement of Ion Concentration

Also used in the NASA rocket was a single-grid ion trap experiment similar to those devised by Boyd [Loeb, 1955] and Pearse and Bennett for the study of gaseous discharges. It consisted of an exposed circular grid with 90 percent transparency behind which is mounted a collector. The latter was biased negatively to remove electron current. The collector current was measured as a function of the retardation potential applied to the grid.

For rocket applications, the ion concentration is computed from the saturated positive ion current for negative values of the grid potential using Eq. 3. This technique is a refinement of the Langmuir probe in that small errors due to electron current are removed. However, a value for \bar{c}_+ , the average ion thermal velocity, must be estimated or assumed before the equation can be used. This computation of ion density also can be made for the positive ion current to the Langmuir probe at negative potentials. Boyd and subsequent observers have found that this positive ion current is governed by the ambient electron temperature. It involves the behavior of the ion velocity vector at the edges of the ion sheath.

The results from NASA 4.07 show that if values of ion current corresponding to the observed electron temperatures [Schulz and Brown, 1955] are used then the computed ion concentrations are within 20 percent of the electron densities measured by the cw propagation technique at altitudes between 130 and 210 km. The data below 130 km has not been analyzed. This is the first direct evidence for equality of the positive ion and electron densities.

The experiment is more adaptable to satellites since when the trap is pointed along the velocity vector, \bar{c}_+ is replaced by the known satellite velocity. It was flown in spherical geometry [Krassovsky, 1954] in Sputnik III. Planar geometry is preferred [Whipple, 1959] for the reasons illustrated in Fig. 6. All four volt-ampere curves are for a medium containing a single ionic constituent (O^+).

Curves A and B represent theoretical cases for satellite potentials of 0 and 4 volts respectively, where the satellite velocity is presumed so much higher than the ion velocity that the latter can be neglected. Curve C was computed [Whipple, 1959] for planar geometry taking into account the ion velocity distribution. Curve D is experimental data from Sputnik III. It is difficult to compute ion concentration from the experimental curve because of the absence of a definite plateau at low retardation potential. Also in spherical geometry, orbital

limited motion can prevent the collection of some of the ions entering the trap.

One of the disadvantages of planar geometry is the susceptibility to photoemission from the collector. It was demonstrated in the NASA rocket that this current can be taken into account by obtaining several volt-ampere curves per roll and by measuring solar aspect.

Conclusions

Four significant results have been obtained by preliminary analysis of data from a September 1959 rocket firing designed to test the accuracy of the following ionospheric environmental-sampling experiments: a radio-frequency impedance probe for the measurement of electron concentration, a Langmuir probe for electron temperature, and an ion trap for positive ion concentration. The techniques are now considered important for studies of ionized regions, including the interplanetary plasma.

The first important result is that all the experiments flown including a supporting electric field meter experiment are internally consistent in describing an ion sheath about twice as thick as expected from simplified kinetic theory. Part of this factor of two is possibly due to rf field disturbances. An accurate knowledge of the sheath characteristics is important,

since this information can be used to improve the accuracy of all environmental sampling techniques.

The second important result is that the accuracy of the electron density measurement by use of the rf probe was improved over previous rocket flights by obtaining data at reduced rf power levels. Electron densities measured in the recent NASA rocket flights by a cw propagation experiment were 1.2 to 1.5 times that obtained by the rf probe at altitudes of 110 km and 210 km, respectively. This remaining discrepancy is explained by an ion sheath having dimensions consistent with those measured by the companion experiments. Hence higher accuracies can be obtained by taking this ion sheath into account.

The third important result is that the single-probe version of the Langmuir probe was found well adapted to the measurement of electron temperatures in the ionosphere. This conclusion is based on the fact that reasonable electron temperatures were obtained on the NASA rocket by use of theories developed by Langmuir and Boyd in their laboratory studies of gaseous discharges. Preliminary data analysis reveal electron temperatures in excess of kinetic gas temperatures measured by other observers at the same latitude but possibly under different atmospheric conditions.

The fourth result is the measurement of positive ion concentrations approximately equal to electron densities experimentally observed from the cw propagation experiment.

The ion concentration values were obtained by using Boyd's observation that the ion current is governed by the ambient electron temperature. This analysis would not apply to ion traps on satellites since in this case the ion collection volume is determined by the known satellite velocity.

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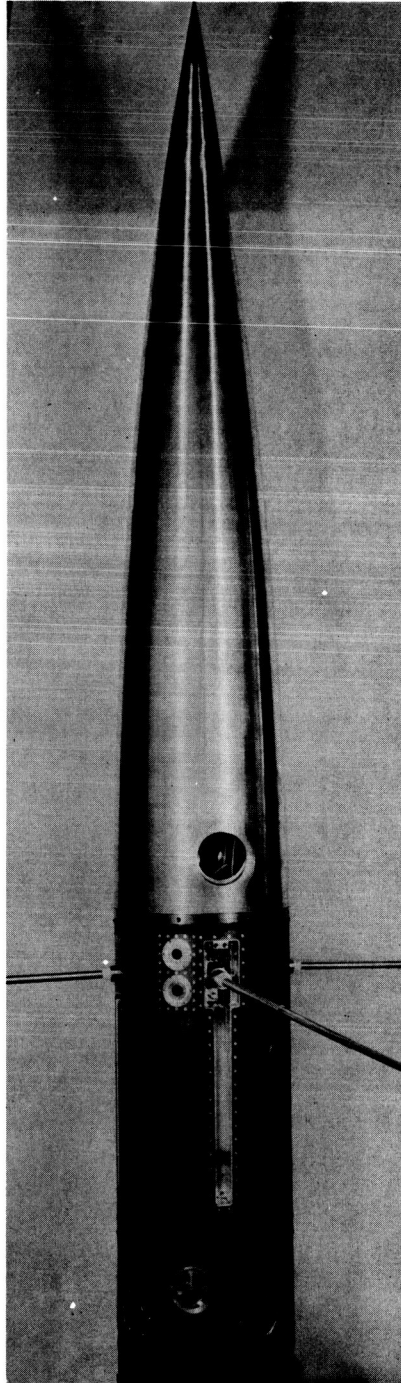


FIGURE 1. NOSE CONE OF NASA AEROBEE-HI ROCKET 4.07,
LAUNCHED 12 SEPTEMBER, 1959

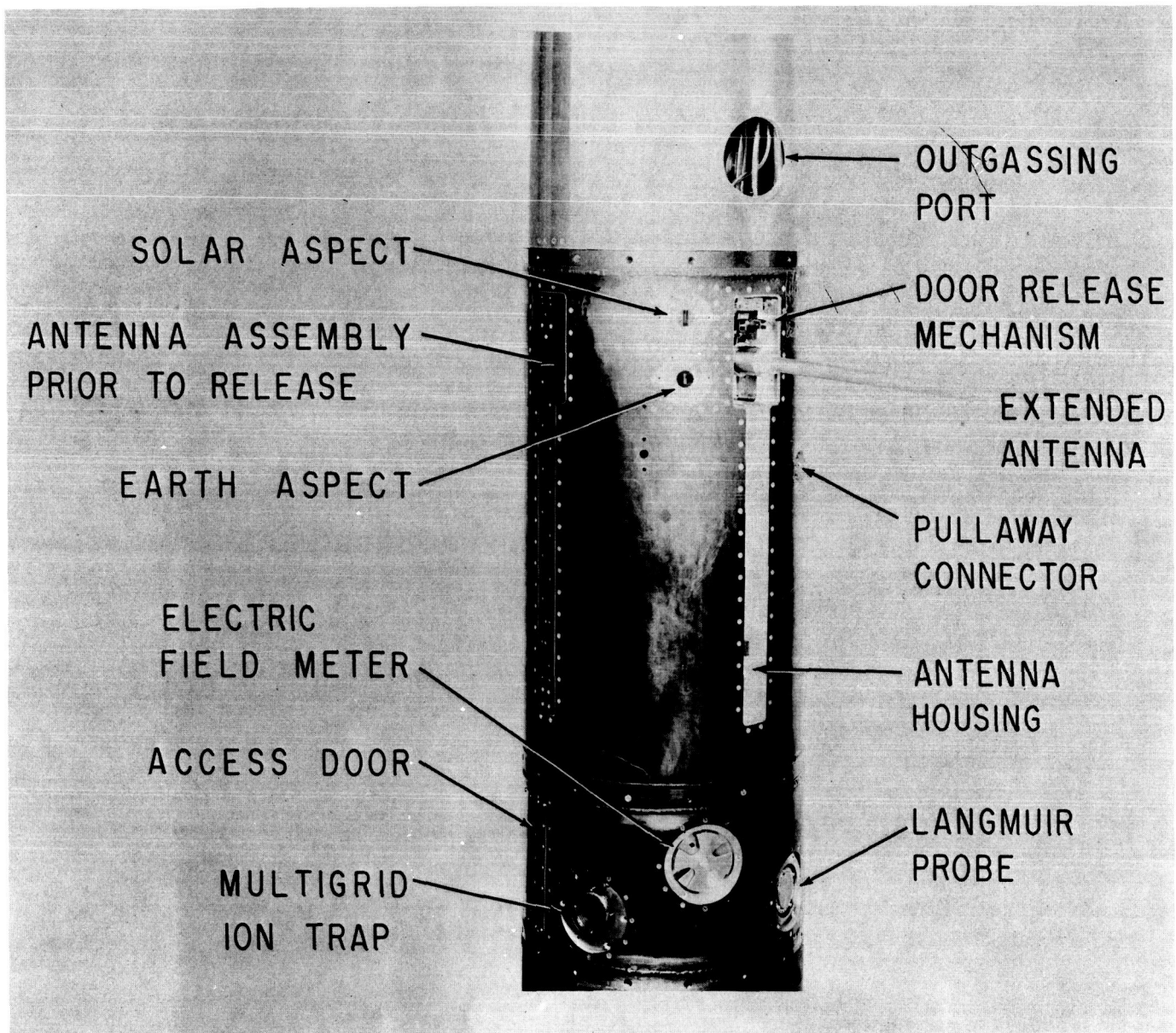


FIGURE 2. SENSOR LOCATIONS. NASA AEROBEE-HI ROCKET 4.07

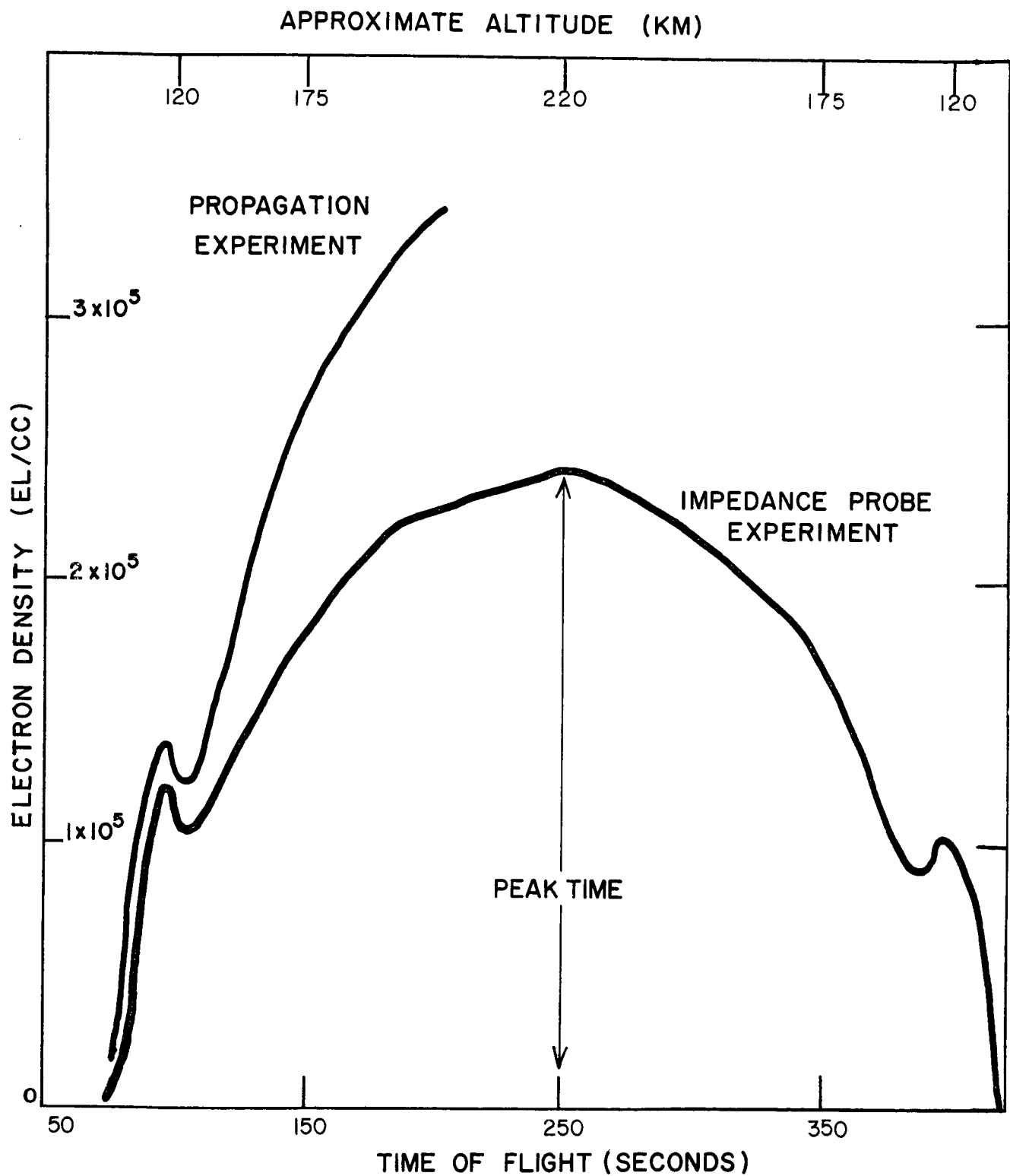


FIGURE 3. ELECTRON DENSITY VS TIME OF FLIGHT
NASA ROCKET AEROBEE 4.07

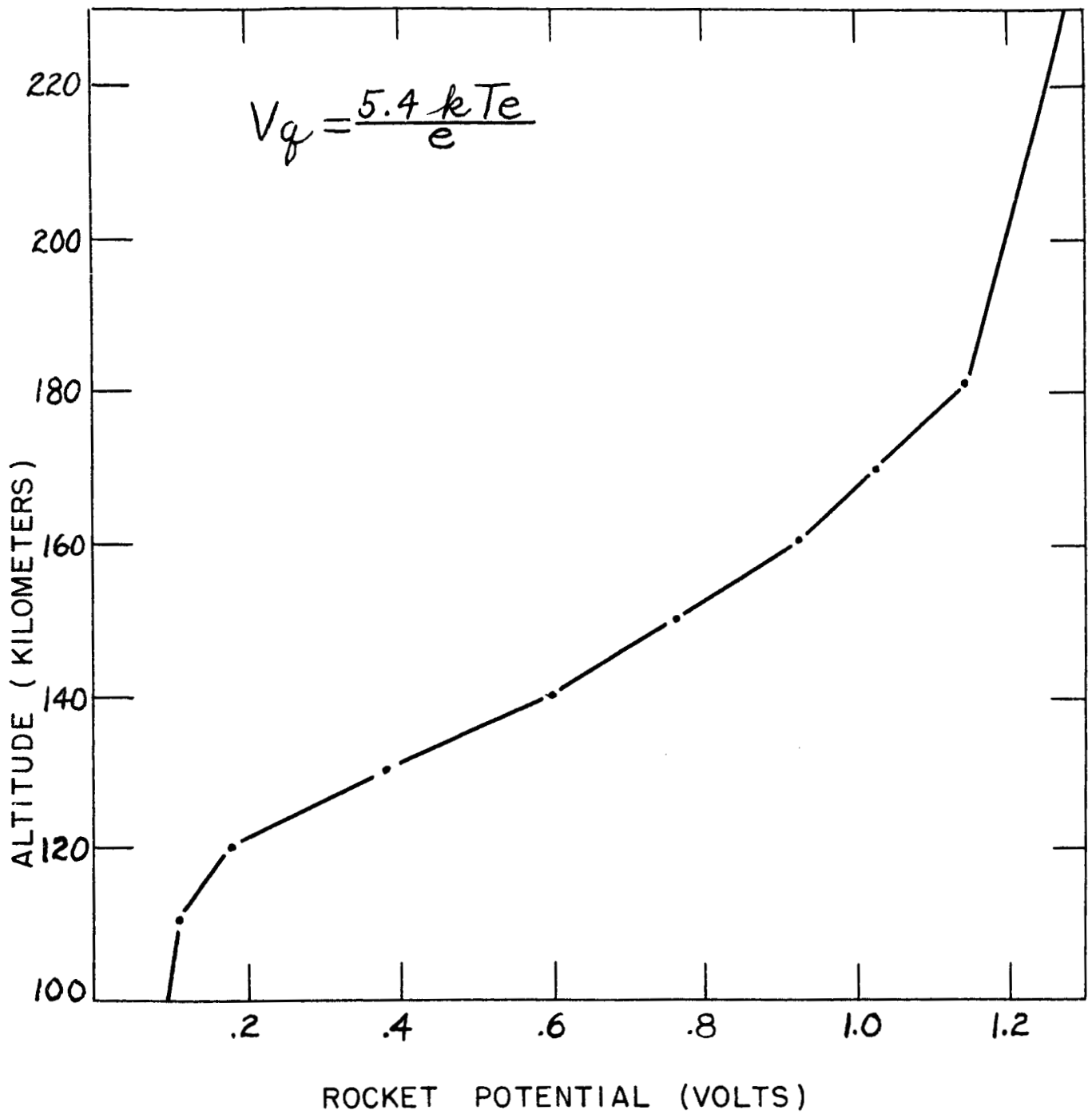


FIGURE 4. ROCKET POTENTIAL (V_g) vs ALTITUDE

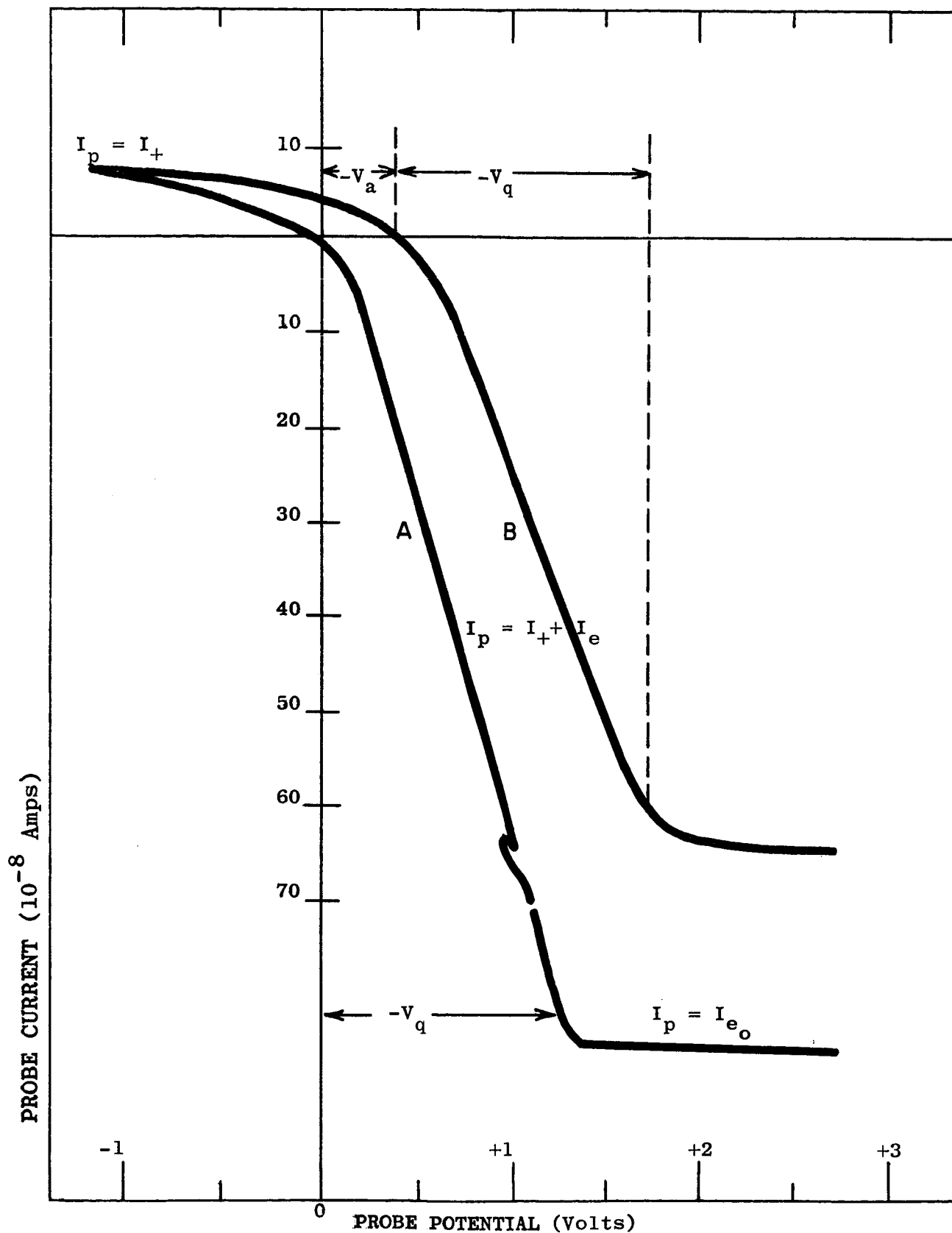
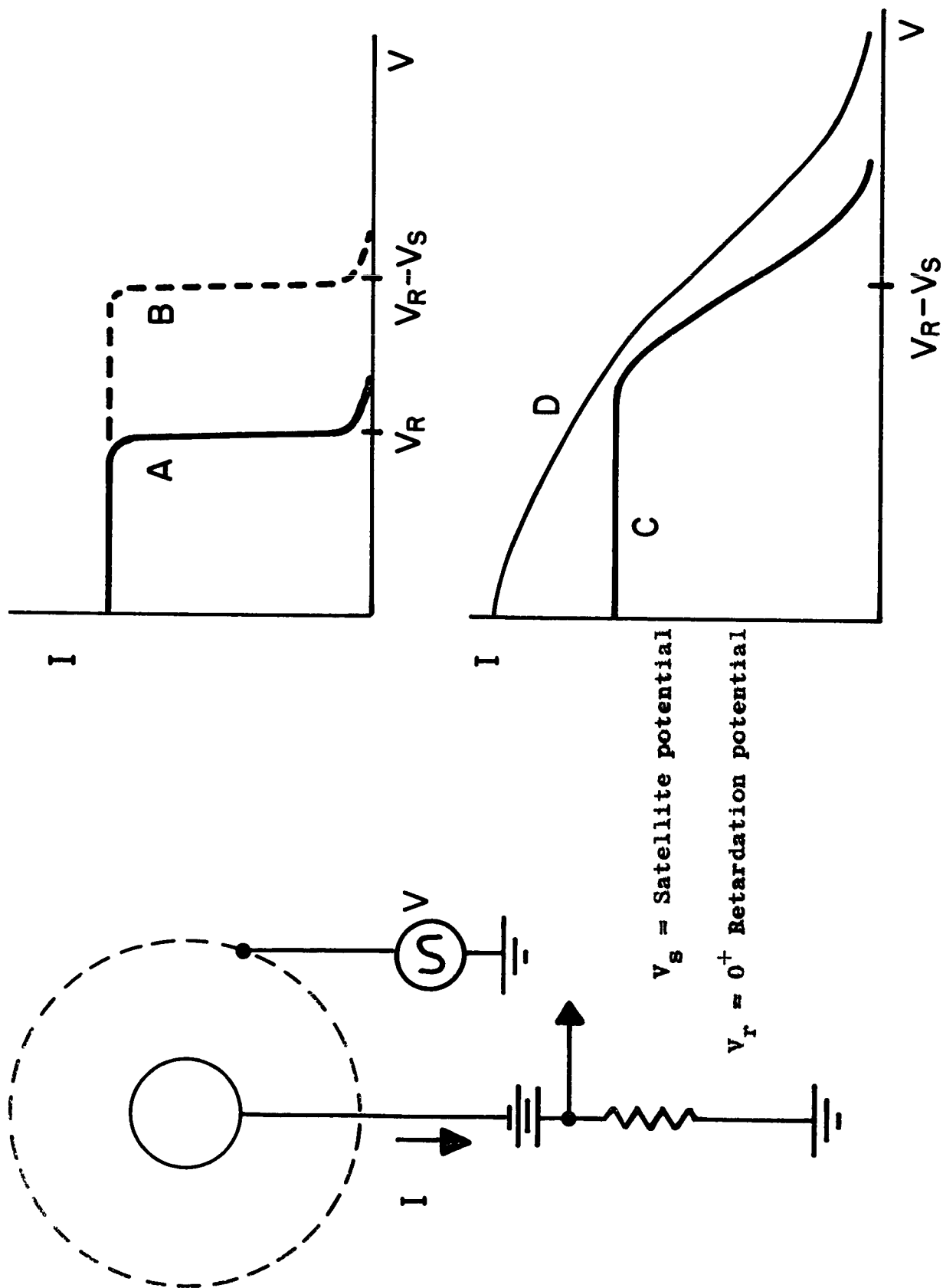


FIG. 5. THEORETICAL (A) AND EXPERIMENTAL (B) LANGMUIR PROBE CURVES AT 180 km.



$V_S =$ Satellite potential

$V_R = 0^+$ Retardation potential

FIG. 6. TYPICAL ION TRAP VOLT-AMPERE CURVES